EXECUTIVE SUMMARY

In response to the Federal Communications Commission (FCC) May 2000 Notice of Proposed Rulemaking [1] concerning the use of ultrawideband (UWB) devices, NTIA Reports 01-384 and 01-389 describe measurements to determine interference potential to global positioning systems (GPS) from UWB devices. Measurements were conducted on four different GPS receivers by combining varying levels of different UWB signals with simulated GPS satellite signals and determining the effects on GPS receiver performance. The results of the first two GPS receivers are described in NTIA Report 01-384 [2] and the results of the second two receivers are described in NTIA Report 01-389 [3]. The primary objective of these measurements was to determine the effects of UWB interference on GPS receivers; a secondary objective was to identify metrics that are reflective of receiver performance for the intended application and to establish repeatable measurement methodologies. The results have provided the technical information needed by NTIA to develop policies for use of UWB by the Federal government [4] and to work with the FCC to develop rules and regulations for UWB emissions.

Background

UWB signals, in general, consist of a sequence of narrow pulses sometimes encoded with digital information. They are characterized by modulation methods that vary pulse timing and position rather than the more conventional techniques of varying frequency, amplitude, or phase. Narrow pulses (on the order of nanoseconds) spread power across a wide bandwidth and reduce power density. UWB proponents argue that the power spectral density decreases below the threshold of narrowband receivers, hence causing negligible interference.

GPS is a powerful enabling technology that has created new industries that are fully dependent upon GPS signal reception. It is presently used in aviation for en-route and non-precision approach landing phases of flight. Precision-approach services, runway incursion, and ground traffic management are currently being developed. On our highways, GPS assists in vehicle guidance and monitoring; public safety and emergency response; resource management; collision avoidance; and transit command and control. Non-navigation applications are often grouped into geodesy and surveying; mapping, charting, and geographic information systems; geophysical measurement and monitoring; meteorological applications; and timing and frequency. Planned systems, such as Enhanced 911, personal location, and medical tracking devices are soon to be commercially available. Moreover, the U.S. telecommunications and power distribution systems are dependent upon GPS for network synchronization timing.

Measurement System

The test setup consisted of three segments – a GPS-source segment, a UWB-source segment, and a GPS-receive segment. The GPS-source segment was further divided into two components – a GPS satellite signal source and a noise source. The GPS satellite signals were generated by a simulator, allowing for repetition of the same satellite constellation over the same simulated date and time. The minimum number of satellites for a receiver to operate nominally, typically four, was chosen. The noise source, emulating the various sources of natural and man-made noise, was combined with the GPS signal to represent a GPS system operating under worst-case, real-world conditions.

GPS receivers were exposed to a broad range of single-source and aggregate UWB signals during the interference measurements. Each UWB signal was injected into the specific GPS receivers operating under worst-case, real-world noise conditions. Aggregate UWB measurements were conducted by combining independent UWB signals to create different multi-source UWB interference scenarios. Each of the individual UWB sources was generated using UWB devices with a pulse narrow enough to produce frequency components in the GPS band. Two types of pulse generators were used, one with a pulse width of 0.500 ns and the other with a pulse width of 0.245 ns. While the shape and width of the two generators are different, the characteristics of the two signals within the GPS band are identical.

The four GPS receivers tested were chosen from a range of different technologies and applications. The first device was a basic receiver used for ground mobile guidance systems. The second device was a high precision surveying receiver that utilizes multiple specialized techniques for improving accuracy. The third device was a reconfigurable receiver used for multiple applications and which employs many of the most modern techniques for signal processing. The fourth device was an enroute aviation receiver. Each of the signals were summed together and fed into an amplifier/filter combination used to emulate the bandwidth and gain of the antenna unit of the respective receiver. The power of the UWB signals was computer controlled, and the entire measurement process was automated for continuous, uninterrupted data acquisition.

UWB Signal Characteristics

Based on information provided by NTIA Report 01-383 [5], a range of signal types were chosen to best represent the range of UWB signal types used in the real world. Thirty-two different types of UWB signals were generated for the single-source measurements by varying the pulse repetition frequency (PRF), pulse spacing mode, and gating. PRF refers to the sequential rate at which the pulses are generated, gating refers to the process of distributing the pulses in bursts, and pulse-spacing-mode refers to the manner in which the pulses are spaced in time with respect to each other. For these measurements, there were four different

PRFs (0.1 MHz, 1 MHz, 5 MHz, and 20 MHz), two types of gating (either 20% duty cycle with a 4 ms pulsed on-time or pulsed on 100% of the time), and four types of pulse spacing (uniform pulse spacing, on-off-keying, absolute-referenced dithering, and relative-referenced dithering). Uniform pulse spacing (UPS), as the name implies, is a pulse train of equal spacing. On-off-keying (OOK) refers to the process of "turning off" certain pulses to represent a binary bit stream. Dithering refers to varying the spacing between pulses, either in relation to a clock reference (ARD) or in relation to the other pulses (RRD).

As an adjunct to the interference measurements, each of the single-source and aggregate UWB signals were characterized for frequency-spectrum and time-varying characteristics. Most noteworthy are the spectral characteristics of the different pulse spacing modes. UPS signals have power gathered up into discrete areas of the frequency spectrum (spectral lines) at intervals equal to the PRF. OOK signals have spectral lines, but they also have a continuous spectral component. Dithered signals can have an entirely smooth spectrum, which is characteristic of Gaussian noise. Gating has the additional effect of spreading the power of spectral lines across a wider area of the frequency spectrum. Time-varying characteristics of each of the UWB signals were summarized using amplitude probability statistics. In the end, UWB characteristics were correlated with GPS receiver performance metrics.

Performance Criteria

The two primary performance metrics for measuring GPS receiver performance were satellite break-lock (BL) and reacquisition time (RQT), where the former is defined as a break in satellite signal tracking and the latter is the time required to reestablish tracking of a satellite signal after BL. These two metrics bracket a region of reduced receiver performance. The associated performance criteria is the maximum UWB signal power below BL for which the GPS receiver can regain satellite signal tracking in a reasonable time, where the definition of "reasonable time" is left to GPS users. The performance criteria must, therefore, be defined by the user, taking into consideration the permissible reacquisition time for the specific application.

Measurement Procedures

BL measurements consist of turning off interference, establishing lock, turning on interference, and sampling the receiver's loss-of-lock indicator once per second over the BL measurement duration (approximately 17 minutes). If the receiver never breaks lock, then the interference power is doubled for the next measurement. Measurements at increasing interference power are repeated until BL occurs. Once BL occurs, interference power is decreased by 1 dB (i.e. a factor of 1.26) until lock is maintained continuously over a measurement duration. The BL point is defined as a point 1 dB greater than the highest interference power that did not cause BL. During BL measurements, the following observational parameters were sampled once per second in order to provide additional information about receiver degradation: pseudorange, observation time, clock offset, carrier phase, Doppler frequency shift, signal-to-noise ratio, potential cycle slip, position data, and receiver tracking status.

RQT measurements consist of turning off the satellite of interest, applying interference, delaying 10 seconds, turning on the satellite, and measuring the number of seconds until the receiver achieves lock. Reacquisition occurs when lock is achieved within 2 minutes and maintained for at least 1 minute. Ten RQT measurements are performed at each interference power level. If reacquisition occurrs at least once, then interference power is increased by 2 dB (i.e. a factor of 1.58). Measurements at increasing interference power are repeated until the receiver never reacquires for all 10 RQT measurements.

Summary of Results

Based on analysis of the acquired data, the following trends were observed regarding UWB characteristics and the associated impact on GPS receiver performance:

1. Any time the UWB signal has a uniform pulse spacing, there are spectral lines, and when these spectral lines lie within the GPS band, there is potential for alignment with spectral lines of the GPS signal. This alignment is particularly invasive; impact is directly related to the magnitude of the specific GPS and UWB spectral lines for which alignment occurs.
2. On-off-keying, since it too has spectral lines, can have a significant impact on GPS receiver performance. However, the effects of OOK are less detrimental than the effects of UPS because the OOK spectral power is distributed between spectral lines and a noise component; hence, the power contained in each line is less.
3. Dithering can reduce the impact of UWB interference on a GPS receiver by reducing or eliminating spectral lines in the GPS band.
4. Higher PRFs have a greater interference effect for two reasons. One reason is that, for those cases with spectral lines, greater power is gathered into each spectral line. The other reason is that higher PRFs result in a greater percentage of time for which the pulses are present.
5. Gating reduces the interference impact on receivers for two reasons. One reason is that the power of individual spectral lines is spread out into multiple lines, thus reducing the power contained in any single line. The other reason is that, for signals of equal gate-on power density, the percentage of time the pulses are present is less with gating.

While there are variations in receiver responses, there are some consistent patterns and notable deviations between receivers. The second receiver deviates the most from the other three since, unlike its counterparts, it is a high precision GPS receiver with a low tolerance for carrier phase discontinuities. The other three receivers show remarkably similar patterns with some slight variations. All three have the same basic BL response to the different UWB signal types. The fourth receiver, however, shows a greater sensitivity to dithered UWB interference which causes BL to occur at lower interference power levels relative to the first and third receivers.

There is a wide range of UWB signal types with a wide range of effects on GPS receivers. Depending upon the bandwidth of the receiver, the PRF, the pulse spacing mode, and the presence of gating, the UWB signal can be impulsive, Gaussian noise-like, or sinusoidal. With PRFs significantly less than the bandwidth of the receiver, UWB interference is impulsive and rarely causes loss of satellite lock. UWB signals with a high PRF and no dithering have strong spectral lines and are most invasive to the receivers. In some cases, the receivers showed significant performance degradation even if they never lost satellite lock. For instance, some gated UWB signals caused an elevated RQT for UWB signal power levels 10,000 times less than the highest interference level in the BL test, even though BL never occurred.

References

[1] *Notice of Proposed Rulemaking*, ET Dkt. 98-153 (rel. May 11, 2000), Federal Register, June 14, 2000, vol. 65, No. 115, pp. 37332 - 37335.

[2] J.R. Hoffman, M.G. Cotton, R.J. Achatz, R.N. Statz, and R.A. Dalke, “Measurements to determine potential interference to GPS receivers from ultrawideband transmission systems,” NTIA Report 01-384, Feb. 2001.

[3] J.R. Hoffman, M.G. Cotton, R.J. Achatz, and R.N. Statz, “Addendum to NTIA Report 01-384: measurements to determine potential interference to GPS receivers from ultrawideband transmission systems,” NTIA Report 01-389, Sept. 2001.

[4] D.S. Anderson, E.F. Drocella, S.K. Jones, M.A. Settle, “Assessment of compatibility between ultrawideband (UWB) systems and global positioning system (GPS) receivers,” NTIA Special Publication 01-45, Feb. 2001.

[5] W.A. Kissick, Ed., “The temporal and spectral characteristics of ultrawideband signals,” NTIA Report 01-383, Jan. 2001.